Chemo-thermo-geomechanical implications for monitoring CCS (and geothermal) reservoirs

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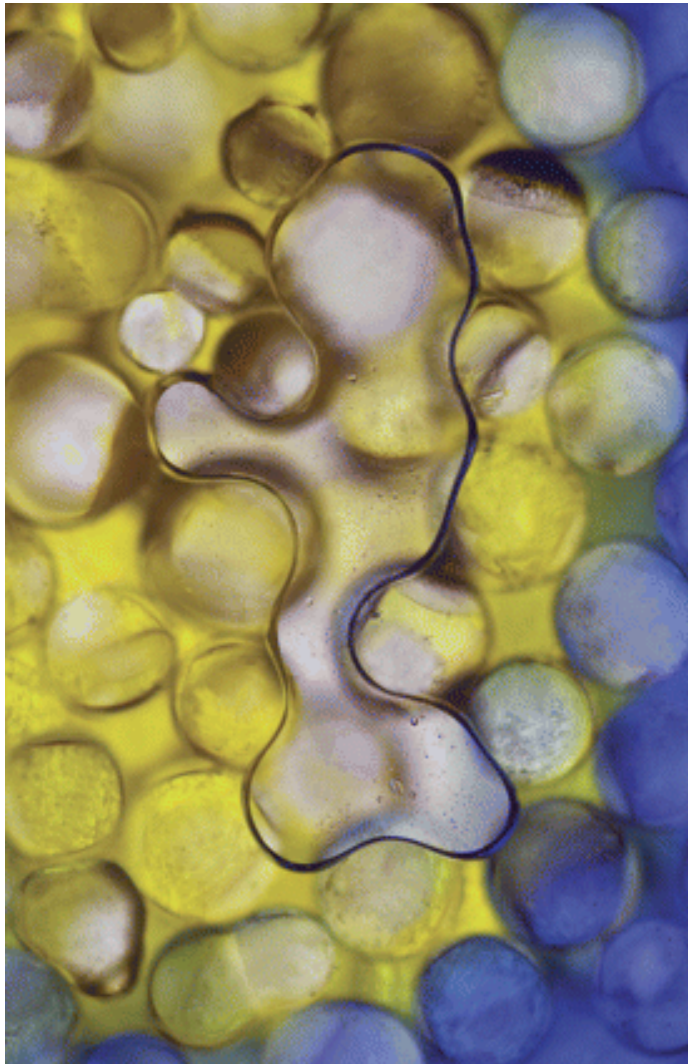

Szulczewski et al. PNAS 2012;109:5185-5189

We Need Abatement, CCS, & Negative Emissions Technologies (NETS) ***at Scale***!


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Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (2019)

DETAILS

510 pages | 7 x 10 | PAPERBACK
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10 Gt/y ~ 80 Gbbl/y storage of sCO_2

Global oil production: 34 Gbbl/y

Global wastewater injection: 100 Gbbl/yr

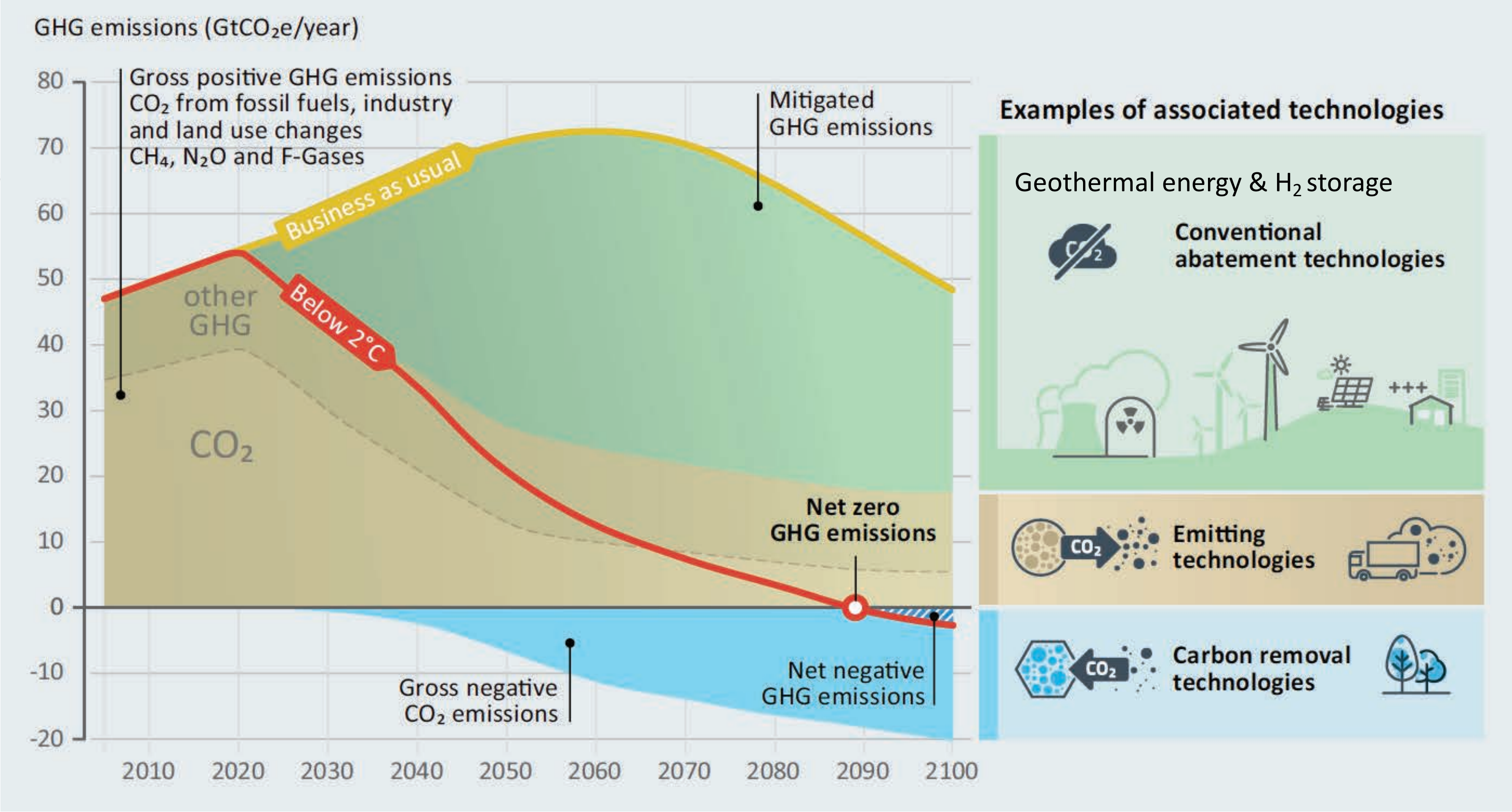
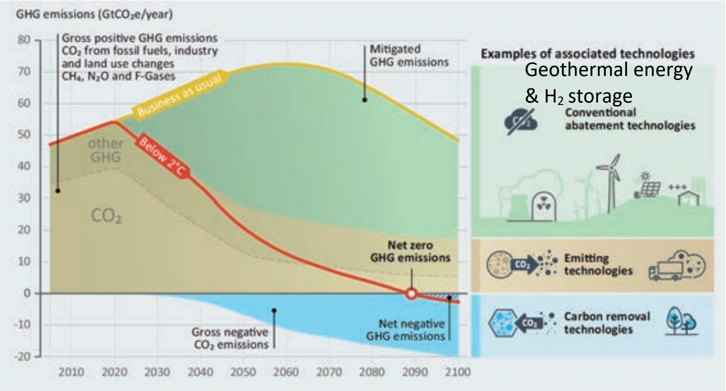


FIGURE 8.1 Scenario of the role of negative emissions technologies in reaching net zero emissions (UNEP, 2017).
NOTES: Green represents mitigation, brown represents anthropogenic greenhouse gas emissions, and blue represents anthropogenic negative emissions. Negative emissions of 10 Gt CO_2 are required by the late 2050s and of 20 Gt CO_2 by the late 2090s because of ongoing positive emissions - ties such as agriculture (mostly N_2O and CH_4) and activities that are very expensive to

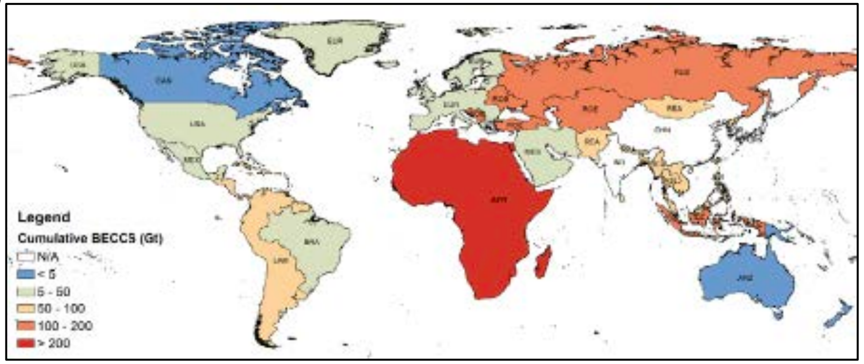
ERL contributions to solution of climate crisis

- Decrease the rate of emissions
  - Geothermal
    - Electricity, low grade heat, . . .
  - Store energy and H_2
  - Carbon Capture and Storage (CCS)

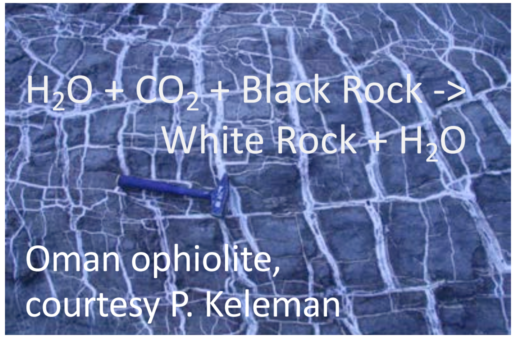


- Remove CO_2 – negative emissions technologies (NET)
  - Bioenergy with CCS (BECCS)
    - Grow biomass, burn, generate electricity, CCS, repeat. . . .
  - Direct Air Capture (DAC)
  - Direct Ocean Capture (DOC)

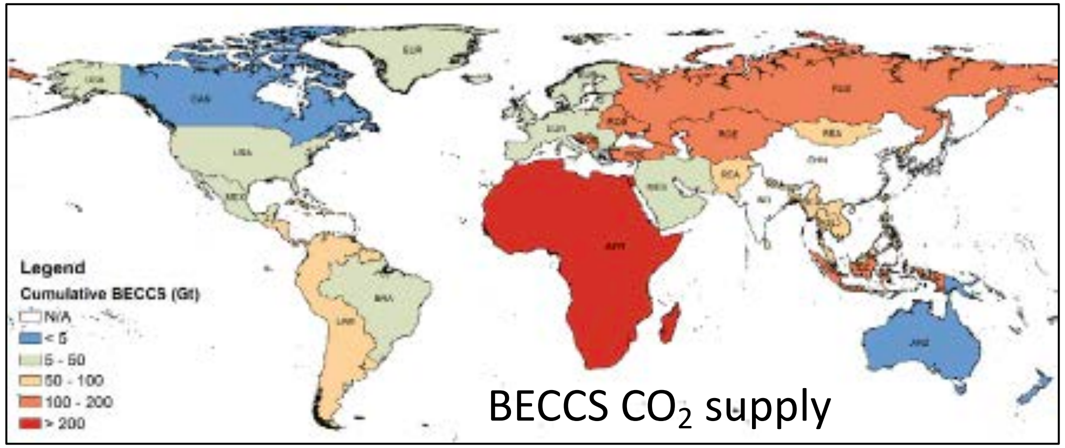
Cumulative CO_2 removal from BECCS under 1.5°C policy with BECCS. 84% of BECCS deployment occurs in developing nations, with 26% alone in Africa.
Fajardy et al., 2020 MITJPGC report



- Geographic distribution of secure storage *at scale* – match to CO_2 capture sites
  - Saline aquifers
  - Mineralization



Matching storage to CO_2 supply *at scale*



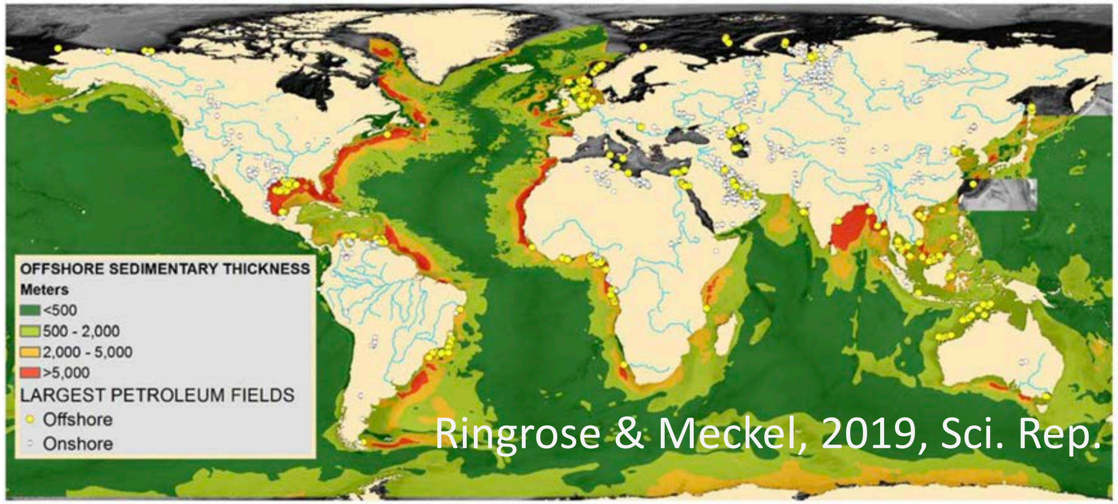
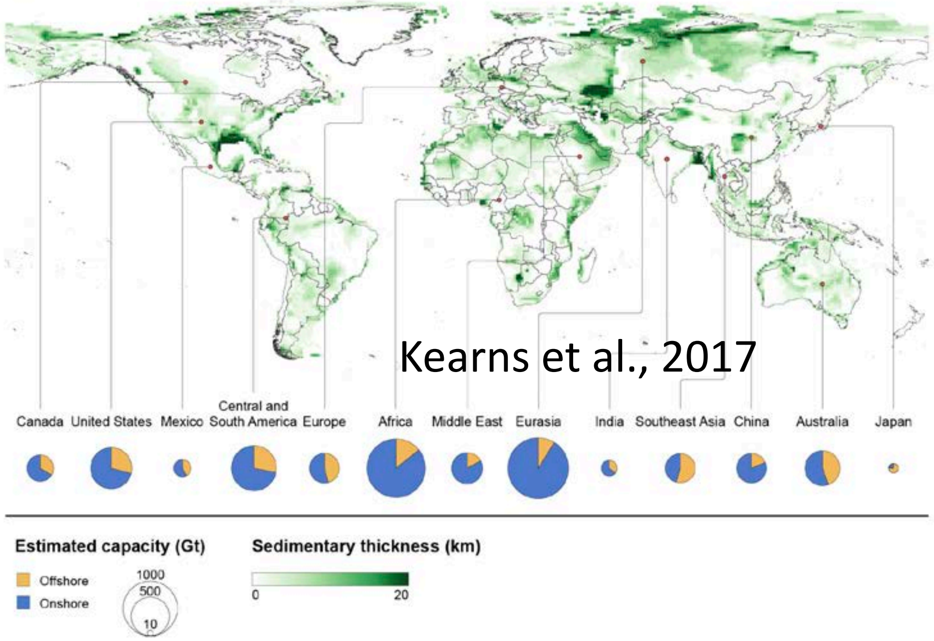
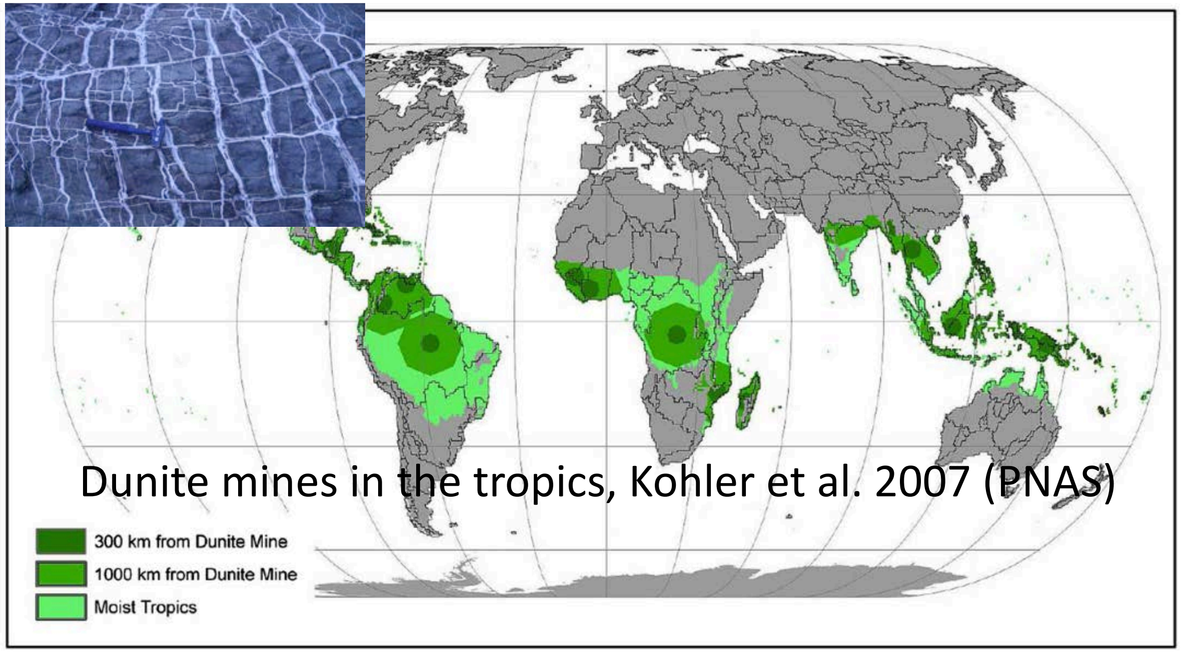


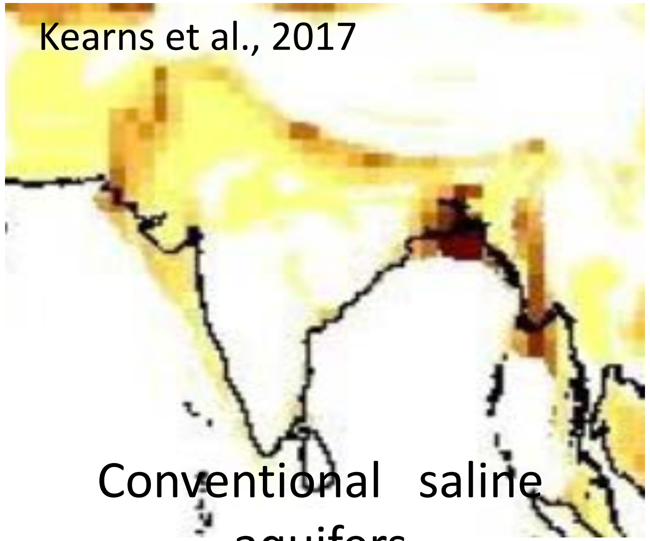
Figure 3.8 Theoretical CO_2 storage capacity by region



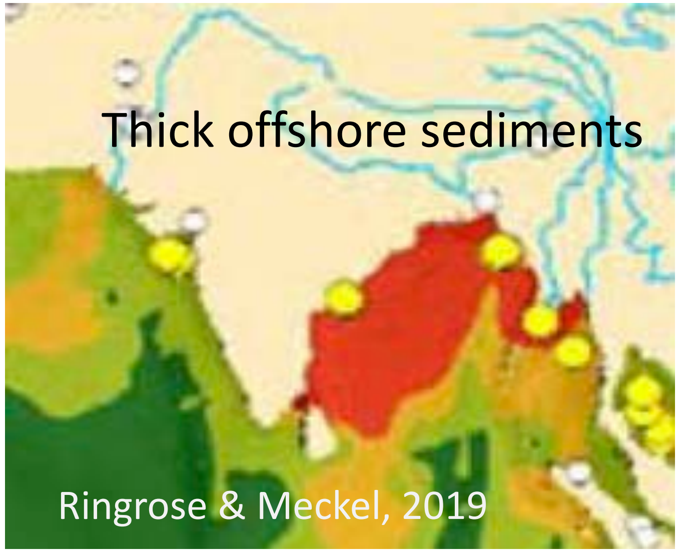


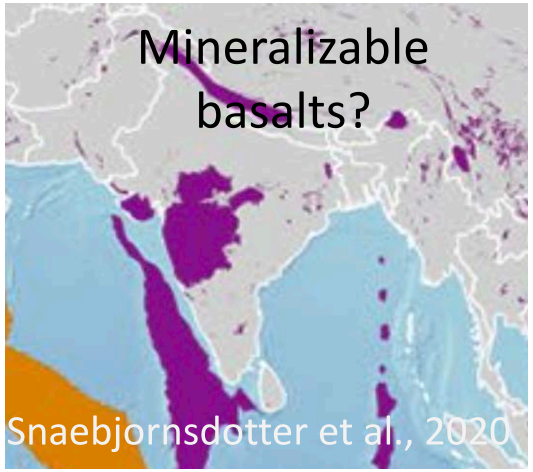
Recognizing storage options is critical for planning

- Example: Is CCS/GSC feasible for India?
  - Not much storage identified on shore
  - Thick offshore deposits, but not well characterized – is it suitable?
    - Exploration, assessment of storage resources
  - Substantial basalt – is it permeable?



aquifers



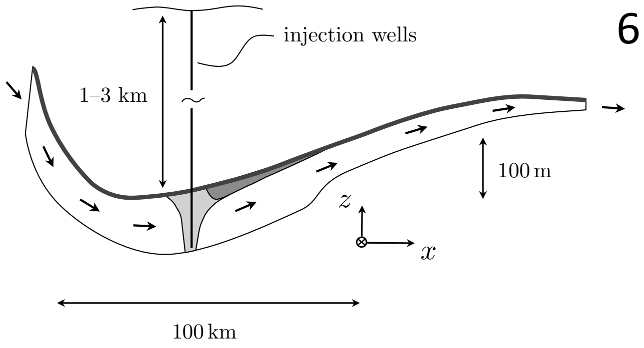


Can permanent CCS be demonstrated?

Role of Geophysics in Carbon Capture and Sequestration
5–7 December 2022 | Saudi Arabia
Abstracts submission deadline: 24 August 2022

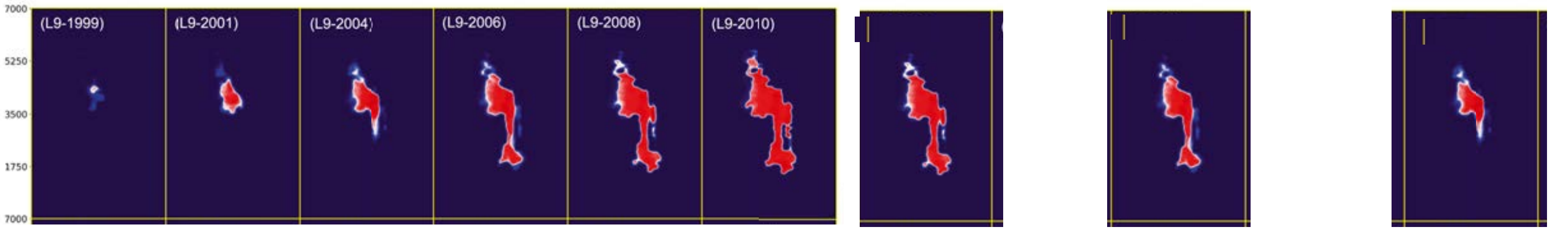
The main challenge for CO_2 Capture is centered around what is called storage permanence. A storage is said to be permanent if it can store 99% of the injected CO_2 for 100 years. Hence, the role of geophysics is to help monitor the status of the injected CO_2 in the reservoir and its capability of storing CO_2 during and after the injection, and to manage the process of the injection itself.

A thought experiment



Szulczewski et al. PNAS 2012;109:5185-5189

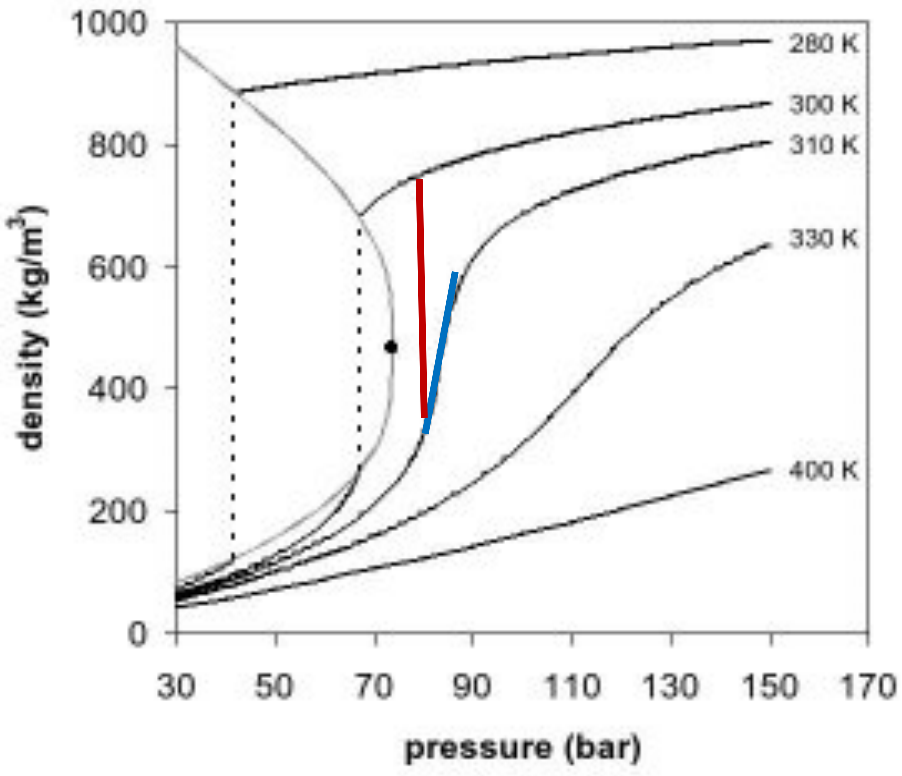
- Inject supercritical CO_2 into a saline aquifer
- Monitor for a few decades (e. g., Sleipner, Li & Li, 2021 JGR)



  - 4D imaging: Plume grows, then begins to shrink
  - Downhole pressure measurements: Increase, then decrease
  - Surface deformation: Uplift, followed by subsidence (InSAR, repeat gravity, . . .)
- Is the reservoir leaking?
  - Walks like a duck, quacks like a duck, ...

- ***Yet these behaviors are expected, even for secure storage***

A key to conventional GCS: rapid increase in CO_2 density with depth



Density of CO_2 increases greatly at ~ 70 bar (700 m H_2O)

Behavior depends strongly on *T* & *P*

Large and variable κ and $\boldsymbol{\alpha}$

$$\kappa_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T$$

$$\alpha = \frac{1}{\rho}\frac{\partial \rho}{\partial T}$$

Nonlinear response

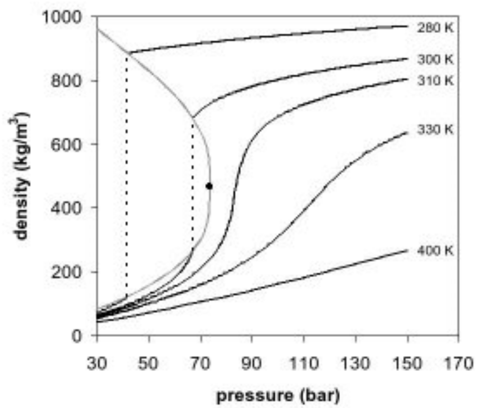
Storage in saline aquifer: important processes

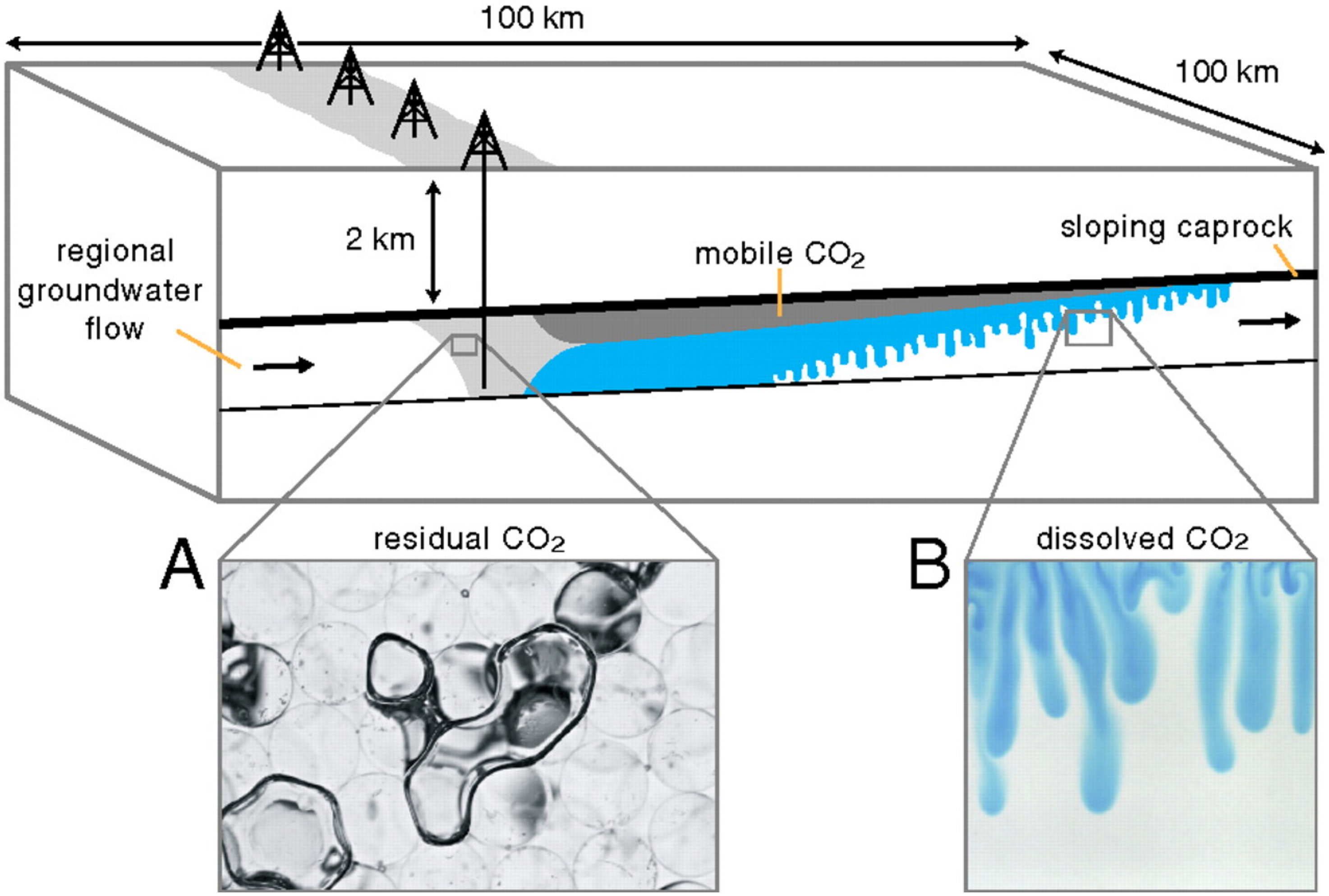
Injection of cold sCO_2 into a hot aquifer
(later T recovery, changes in V and P)

Trapping of some CO_2 in pores & throats
(changing solubility as T and P change)

Ponding of sCO_2 beneath caprock
(changing κ and α as T and P change)

CO_2 dissolves in brine and sinks
Plume shrinkage expected!





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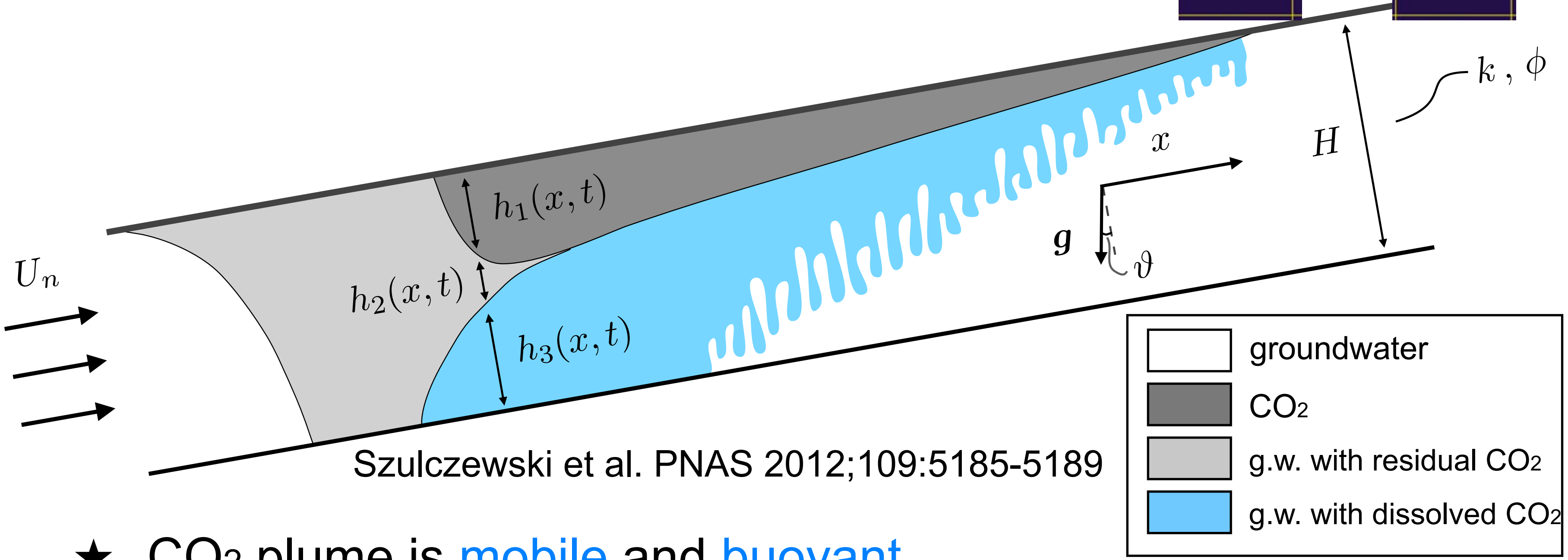
Plume Migration: Post-injection



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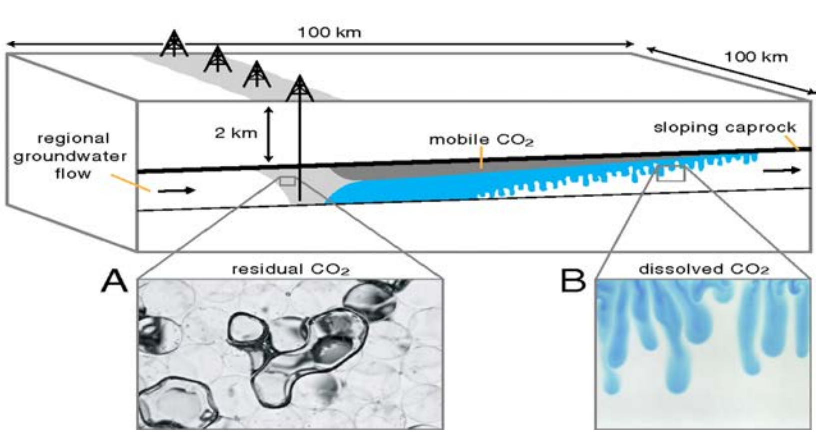
★ CO_2 plume is mobile and buoyant

- Plume migrates due to groundwater flow and aquifer slope
- Plume spreads due to buoyancy
- Plume shrinks due to capillary trapping
- Plume shrinks due to dissolution

Brine with dissolved CO_2 ~ 3-5 % denser than before dissolved

Chemo-elasticity: ΔV & Δp changes



- Dissolution
    - Easily misinterpreted as leakage
    - Large effects on in situ κ and $\boldsymbol{\alpha}$
- Mineral replacement – large ΔV
    - Effect on permeability?
        - Pore clogging?
        - Carbofracking?
            - Seismicity?

Dissolution reactions: Calcite, siderite, magnesite….

Basaltic rock + xH^+ ….→ $Mg^{2+} + Ca^{2+} + Fe^{2+} + Al^{3+} + SiO_{2(aq)}$…

$Mg_2SiO_4 + 4H^+ \rightarrow 2Mg^{2+} + 2H_2O + SiO_{2(aq)}$

$Fe_2SiO_4 + 4H^+ \rightarrow 2Fe^{2+} + 2H_2O + SiO_{2(aq)}$

Precipitation reactions:

$(Ca,Mg,Fe)^{2+} + CO_3^{2-} \rightarrow (Ca,Mg,Fe)CO_3$

(calcite, siderite, magnesite……)

Summary – looking forward

- CCS is essential to mitigate large temperature increases
  - Near term: Decrease rate of emission of CO_2 into the atmosphere
  - Long term: Remove CO_2 from the atmosphere - net negative emissions
- The scale needed is daunting
  - > than current rate of wastewater injection and hydrocarbon production
- Sources of CO_2 will be distributed unevenly globally, storage sites must match
  - Much more exploration and characterization are needed
    - Shallow reservoirs may be best (high porosity and permeability, lower risk of leakage & sseismicity)
- It is not feasible to demonstrate 99 % containment
  - Successful storage sites are easily misidentified as leaking!
  - Tolerating minor leakage less damaging than stopping storage
  - Regulations should be based on detecting leaks, rather than proving containment